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RESEARCH ARTICLE

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Effects of nitrogen and phosphorus fertilizer on crop yields in a field pea-spring wheat-potato rotation system with calcareous soil in semi-arid environments

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Abstract

The object of the present study was to investigate the yield-affecting mechanisms influenced by N and P applications in rainfed areas with calcareous soil. The experimental treatments were as follows: NF (no fertilizer); N (nitrogen); P (phosphorus); and NP (nitrogen plus phosphorus) in a field pea-spring wheat-potato cropping system. This study was conducted over six years (2003-2008) on China's semi-arid Loess Plateau. The fertilizer treatments were found to decrease the soil water content more than the NF treatment in each of the growing seasons. The annual average yields of the field pea crops during the entire experimental period were 635, 677, 858, and 1117 kg/ha for the NF, N, P, and NP treatments, respectively. The annual average yields were 673, 547, 966, and 1056 kg/ha for the spring wheat crops for the NF, N, P, and NP treatments, respectively. Also, the annual average yields were 1476, 2120, 1480, and 2424 kg/ha for the potato crops for the NF, N, P, and NP treatments, respectively. In the second cycle of the three-year rotation, the pea and spring wheat yields in the P treatment were 1.2 and 2.8 times higher than that in the N treatment, respectively. Meanwhile, the potato crop yield in the N treatment was 3.1 times higher than that in the P treatment. In conclusion, the P fertilizer was found to increase the yields of the field pea and wheat crops, and the N fertilizer increased the potato crop yield in rainfed areas with calcareous soil.

Additional key words: water use efficiency; available phosphorus; semi-arid Loess Plateau.

Abbreviations used: AP (available phosphorus); CY (crop yield); ET (evapotranspiration); MN (mineral nitrogen); NF (no fertilizer); NP (nitrogen and phosphorus); PGS (precipitation in growing season); SOC (soil organic carbon); SWH (soil water content at harvest); SWS (soil water content at sowing); TN (total nitrogen); TP (total phosphorus); WUE (water use efficiency).

Authors' contributions: Conceived and designed the experiments, performed the experiments, and wrote the paper: CAL. Analyzed the data: SZ, SH, XR. Contributed reagents/materials/analysis tools: CAL, SH.

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Introduction

The soil's water content is critical for sustaining rain-fed agriculture in semi-arid areas (Ucar *et al*., 2009; Sileshi *et al*., 2011; Frank & Viglizzo, 2012; Abdullah, 2014; Liu *et al*., 2014). The precipitation is the main water source for crop production in these types of regions (Liu *et al*., 2013a; Mhizha & Ndiritu, 2013). Liu *et al*. (2013a) reported that an application of manure conserved the soil water in the 0 to 100 cm soil layer more effectively than fertilizer treatments in semi-arid environments (280 mm rainfall). Huang *et al.* (2003) reported that winter wheat monocultures with high fertilization (120 kg/ha N and 60 kg/ha P_2O_5) did not appear to be sustainable practices with regards to the soil water depletion in a region where average annual precipitation was 584 mm, and 285 mm occurred in growing season.

In semi-arid areas, the crop yields are generally very low due to the minimal supply of soil water and nutrients (Liu *et al*., 2013b; Hernanz *et al*., 2014; Kurwakumire *et al*., 2014). Also, low crop productivity results in less crop residue and stubble being returned to the soil (Liu *et al*., 2013b; Singh *et al*., 2015). It is known that N and P are the most essential plant nutrients with respect to maintaining soil fertility and increasing crop yields (Zougmoré *et al*., 2004; Romanyà & Rovira, 2009; Morell *et al.,* 2011; Zhou *et al*., 2013). Nieder & Benbi (2008) reported that over 90% of the N in most surface soil occurs in organic forms, and is coupled with soil organic carbon (SOC). A soil's N content is often limited in semi-arid areas due to the lower crop residue (Zhou *et al*., 2013). The high pH in calcareous soil generally increases the NH_3 volatilization (Li & Liu, 1993) and decreases the N use efficiency. The deficiency of P in soil is generally caused by a low total P content, or a low bioavailability of P in the soil (Ramaekers *et al*., 2010). The availability of P is often affected by the soil type and pH levels, as well as agricultural fertilizer and tillage practices (Von Wandruska, 2006; Hu *et al*., 2012; Liu *et al*., 2013b). Phosphate anions are highly reactive, and can be immobilized through sorption and/or precipitation with cations, such as Ca^{2+} and Mg^{2+} (Wang, 1992). In calcareous-alkaline soils, the $CaCO_3$ content is high, and the P fertilizers mainly contain the less available form of Ca_8-P (Wang *et al*., 2005). In the semi-arid Loess Plateau of China, the problem is not always due to a lack of P reserves in the soil. There is also the factor of the P content being unavailable to the plants with high soil pH (Li *et al*., 2008). In the P-depleted areas of Argentina, P fertilizer input is important for maintaining the soil's available P content, as well as improving wheat crop yields (Covacevich *et al*., 2007; Barbieri *et al*., 2014).

In China, field pea *(Pisum sativum* L.), spring wheat (*Triticum aestivum* L.) and potato (*Solanum tuberosum* L.) are important crops grown in the semi-arid regions (250 to 400 mm rainfall) (Xiao *et al*., 2007; Liu *et al*., 2013a). However, there have to date been little data available regarding the yield-increasing mechanisms and soil fertility responses to N and P fertilizers used for these crops in calcareous-alkaline soils. The objectives of this study were to investigate the responses of the soil's water, crop yields, and soil fertility to N and P fertilizers in calcareous soil in a semi-arid area.

Material and methods

Experimental site

In this study, a field trial was conducted from April, 2003 to September, 2008 at the Semi-Arid Ecosystem Research Station of Lanzhou University on the Loess Plateau (36°02 N, 104°25 E, 2400 m above sea level) in ZhongLianChuan, which is located in the northern mountainous region of Yuzhong County, Gansu Province, China. The site has a medium-temperate semi-arid climate, with a mean annual air temperature of 6.5°C, and mean maximum and minimum temperatures of 19.0°C (July), and -8.0°C (January). The average annual free-water evaporation was determined to be ~1300 mm. The mean annual precipitation was 320 mm, of which ~ 56% was received between July to September. Due to the fact that the water table was below 60 m, the groundwater was not available for plant growth. The soil had a mean soil bulk density of 1.15 g/cm^3; soil pH of 8.0; 11.5 g/kg of soil organic C; 1.2 g/kg of soil total N; 0.72g/kg of soil total P; 5.3 mg/kg of available P; 102.5 mg/kg of available K; and 142 g/kg of $CaCO_3$ in the 0 to 20 cm soil layer at the beginning of the experiment. The soil was Heima, Calcic Kastanozems (FAO taxonomy) with afield water holding capacity of 22.9%, and a permanent wilting coefficient of 6.2% (Shi *et al*., 2003).

Experimental design and field management

Prior to the experiment conducted in 2002, the site had been planted with potato, which was harvested and then followed by a fallow period of 160 days before the field pea crop was sown in 2003. The fertilizer regime commenced in April 2003 and was comprised of four treatments as follows: (1) NF (control), no fertilizer; (2) N, N applied as urea at 70 kg N/ha each year; (3) P, P applied as superphosphate at 15.7 kg P/ha each year; and (4) NP, N+P at the same rates as above each year. In this study, large agricultural farming machines could not be applied due to the relatively small size of the fields. The fields were ploughed flat, and the fertilizers were incorporated into the soil using spades each October from 2003 to 2007, and also before the crops were sown in 2003. The fertilization treatments were arranged in a randomized block design with three replicates. Each plot was 30 m^2 (5 m×6 m), with the total experimental area being 360 m^2 (12 plots). Then, a bare ridge (100 cm wide, 40 cm high) was raised between every two plots to prevent runoff.

The field pea (cv. 'Yannong 2'), spring wheat (cv. 'Heshangtou'), and potato (cv. 'Xindaping 1') crops, in this sequence, were grown in rotation for the six-year period from 2003 to 2008 (Table 1). It is known that cvs.'Yannong 2' (field pea) and 'Heshangtou' (spring wheat) have strong ecological adaption abilities for drought tolerance (for example, developed root systems), with growth periods of 120 days. 'Xindaping 1' (potato) has a high starch content (up to 20% of its total weight), and a growth period of 150 days. In this region, the crops are seldom harmed by injurious insects due to the arid climate. Therefore, no pest control methods were used in this rotation system. The planting dates, seeding rates, seeding depths, and harvest dates for each of the crop are shown in Table 1.

Sampling and measurements

The crop samples were harvested by hand at maturity from a 12 m² area at the center of each plot. All plant part samples (leaves, stems, and roots), grain and/or tubers were oven-dried at 105°C for one hour, and then at 70°C for a minimum of 72 hours (Jia *et al*., 2006; Peng *et al*., 2011). In this study, the crop yield refers to the grain yield of the spring wheat and field pea, or the dry weight of the tuber yield of the potato crops. The aboveground biomass refers to the total biomass removed from the field by the farmers. The plant tissue samples of the potato tubers, and the aboveground biomass or field pea/wheat grain and straw were collected at maturity. The sample plants were oven-dried for dry matter content at 60°C for 48 hours, and then ground and analyzed for total nutrient concentrations.

The total nitrogen (TN) content of the tissue samples was measured by using a dry combustion method with a CHNS-analyzer (Elementar Vario El, Elementar Analysensysteme GmbH, Hanau, Germany). The total phosphorus (TP) content was determined colorimetrically following digestion with perchloric acid.

The soil moisture level was determined gravimetrically to a depth of 200 cm at the beginning and end of each growing season, using a soil auger (8 cm diameter, 20 cm high), and there were three auger samples taken per replicate plot.

The apparent water use during the growing period, expressed as evapotranspiration (ET, in mm), was calculated from the precipitation during the growing season (PGS) and soil water consumption data during the growing periods. The soil water content at sowing (SWS) and the soil water content at harvest (SWH), both in mm, were calculated as the gravimetric moisture content (soil water × soil bulk density × thickness of soil layer). The experimental field was a terrace, and a bare ridge (100 cm wide, 40 cm high) was raised between every second plot to prevent runoff. The loess soil had a good water holding capacity, with the upper 200 cm storing all of the annual rainfall (Li & Li, 1995). Therefore, it was assumed that no drainage occurred below this depth during the experiment (Liu *et al*., 2009, 2013a). In addition, irrigation water was not applied, and the following simple equation was used to calculate the ET:

$$ET = SWS + PGS - SWH$$

The water use efficiency (WUE, in kg/ha · mm) was calculated from the crop yield (CY) and ET according to the following:

$$WUE = \frac{CY}{ET}$$

In each plot, three soil cores (diameters of 8 cm, and heights of 20 cm) were randomly obtained before the crops were sown each year. The samples were air-dried, ground, sieved (2 mm and 0.9 mm), and stored at room temperature until required. The available phosphorus (AP) content was determined using the Olsen *et al*.'s (1954) method. Then, the dried samples weighing 10 g each were added to 50 mL of 2 M KCl, shaken for 1 hour, and analyzed with a FIAstar 5000 Analyzer (FOSS Tecator, Sweden) in order to obtain the nitrate nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) levels.

Statistical analysis

The analysis of the variance (ANOVA) was conducted using an SAS package (SAS Inst., 1990). The comparisons were made by the least significant difference (LSD) at $p \leq 0.05$.

Table 1. Rotation sequence, planting date, seeding rate, depth of seeding, and harvest date for the crops grown in the experiment.

Year	Crop	Planting date	Seeding rate (kg/ha)	Depth of seeding (cm)	Harvest date
2003	Pea	Early April	135	4	Early August
2004	Spring wheat	Early April	180	3	Early August
2005	Potato	Late April	1500 (fresh tuber)	10	Late September
2006	Pea	Early April	135	4	Early August
2007	Spring wheat	Early April	180	3	Early August
2008	Potato	Late April	1500 (fresh tuber)	10	Late September

Results

Crop growing period, precipitation, and air temperature

In this study, the potato crop had the longest growing period which averaged ~150 days, followed by field pea and wheat at ~ 120 days. The precipitation during the potato crops' growth period accounted for ~ 80% of the total annual precipitation, while for the field pea and wheat, and it was ~ 50% (Fig. 1). Most of the precipitation was determined to have occurred between July and September. The years 2004, 2006, and 2008 were dry years, registering between 202 and 254 mm; 2003 and 2005 were average years, with 315 and 316 mm, respectively; and 2007 was a wet year, with 390 mm (Fig. 1). The average air temperatures during all of the treatments changed from 7.7 to 8.4°C from 2003 to 2008. The average maximal air temperatures in all of the treatments changed from 21.0 to 23.1°C from 2003 to 2008. The average minimal air temperatures in all of the treatments changed from -6.5 to -3.0°C from 2003 to 2008 (Table 2). The growing seasons' precipitation were 151.2, 118.5, 262.2, 88.5, 225.5, and 201.5 mm for the years 2003, 2004, 2005, 2006, 2007, and 2008, respectively (Table 3).

Soil moisture, crop yield, and water use efficiency

In the 0 to 200 cm soil layer, the soil's water content was always higher in the NF treatment are as compared with the fertilizer treatments from April, 2005 to September, 2008 (Fig. 2). The average soil water content

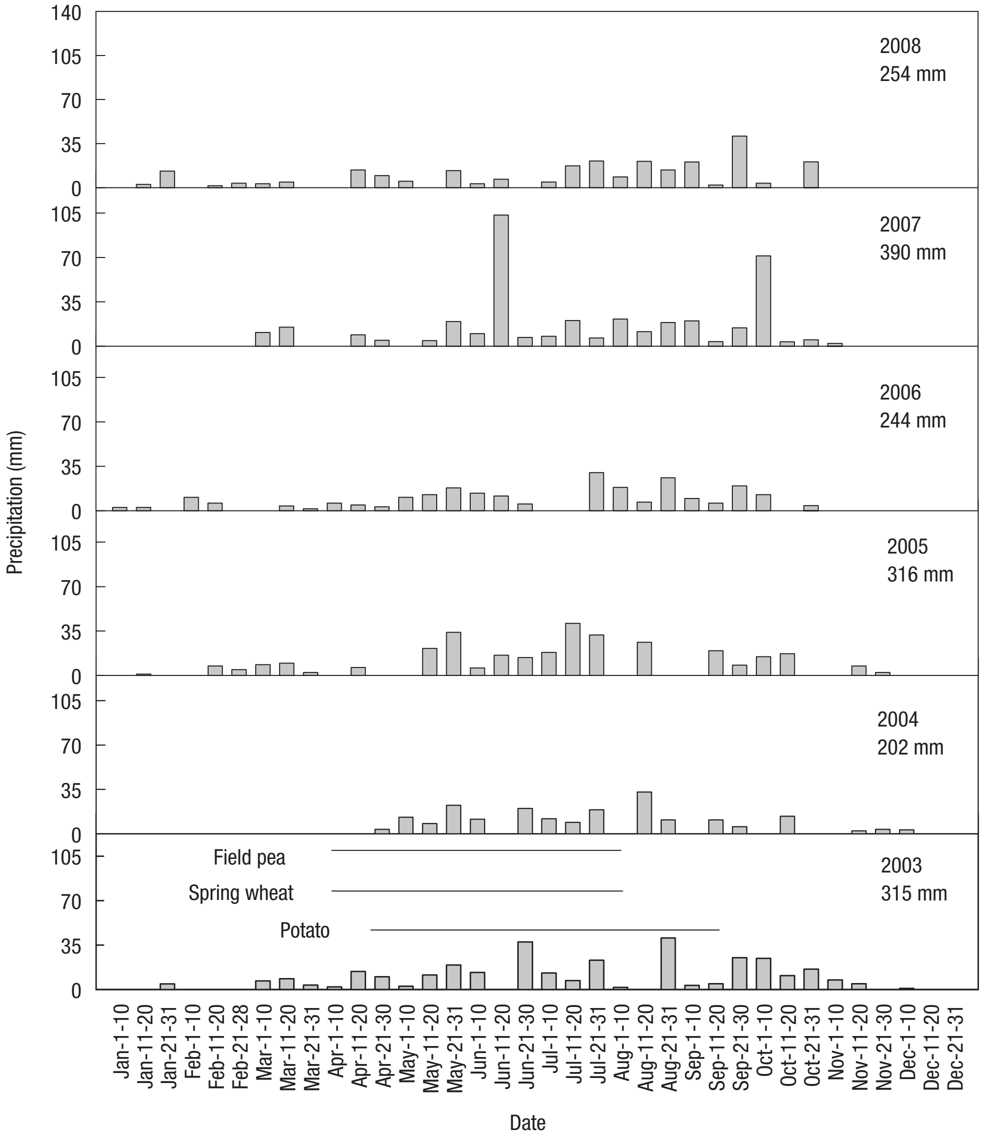

Figure 1. Distribution of precipitation at the study site (calculated every 10 days) during the six-year experiment (2003 to 2008), and the crop growth periods (field pea, spring wheat, and potato).

Table 2. Average, maximum, and minimum air temperatures during the six-year experiment.

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year avg.
Average temperature (°C)	2003	–5.9	–0.2	3.6	8.2	13.8	17.6	19.1	18.0	14.2	7.2	1.4	–4.3	7.7
	2004	–5.6	–2.1	3.8	11.3	13.4	16.8	18.9	18.5	13.7	7.4	0.4	–3.4	7.8
	2005	–5.9	–3.1	2.8	9.6	14.2	18.8	19.4	18.1	15.2	7.0	1.3	–4.3	7.8
	2006	–4.4	–2.1	3.2	9.7	14.2	18.7	22.0	20.1	12.9	10.7	2.7	–6.6	8.4
	2007	–6.5	1.0	3.4	8.7	16.7	17.7	19.0	19.4	13.3	6.9	2.5	–2.8	8.3
	2008	–8.3	–6.2	5.7	10.1	15.5	18.4	20.2	17.9	14.1	9.1	1.6	–4.1	7.8
Maximum temperature (°C)	2003	11.5	14.0	26.7	24.1	26.0	29.3	30.5	28.7	25.7	19.3	20.7	7.4	22.0
	2004	11.2	15.3	25.2	28.7	28.5	30.9	31.4	29.6	26.7	19.7	17.4	12.5	23.1
	2005	7.6	10.5	16.7	25.8	26.6	29.7	32.0	28.8	28.1	20.9	17.6	7.2	21.0
	2006	12.7	12.0	19.6	29.3	29.8	31.6	31.3	31.3	24.0	22.4	17.9	10.7	22.7
	2007	11.1	16.7	26.1	26.2	31.2	29.6	29.6	30.3	24.8	16.4	15.6	10.0	22.3
	2008	10.3	11.2	20.4	28.3	28.1	31.4	30.6	30.3	25.6	22.1	15.7	12.1	22.2
Minimum temperature (°C)	2003	–20.1	–13.7	–10.5	–3.5	3.1	6.0	10.5	7.9	3.7	–2.5	–8.9	–14.1	–3.5
	2004	–18.4	–19.9	–13.5	–4.7	–2.8	5.7	7.6	8.6	3.8	–4.2	–16.2	–20.4	–6.2
	2005	–17.2	–14.2	–10.8	–4.1	1.7	9.5	10.6	9.9	6.5	–3.7	–10.9	–17.4	–3.3
	2006	–18.4	–15.9	–12.2	–6.6	1.0	8.3	11.0	9.6	2.8	0.7	–9.2	–15.1	–3.7
	2007	–16.3	–13.5	–10.7	–4.6	2.7	8.8	9.1	9.6	3.9	–1.9	–8.5	–14.7	–3.0
	2008	–23.9	–21.6	–6.2	–2.5	3.1	7.2	8.4	7.1	5.0	–0.9	–12.3	–13.7	–4.2

Table 3. Precipitation during the growing seasons (PGS), evaporanspiration (ET), annual aboveground biomass (AB), crop yields, and water use efficiency ($WUE_{Y/ET}$) of the crop yields in various treatments at the 0 to 200 cm soil layers during the six-year experiment.

Crop	Year	Treatments	PGS (mm)	ET[1] (mm)	AB (kg/ha)	Yield (kg/ha)	$WUE_{Y/ET}$ (kg/ha/mm)
Pea	2003	NF	151.2	149.2a	2045c	854c	5.8b
		N	151.2	153.3a	2217c	927c	6.2b
		P	151.2	158.6a	2774b	1220b	7.8b
		NP	151.2	164.5a	3912a	1674a	10.4a
Spring wheat	2004	NF	118.5	147.2a	2475c	542c	3.7b
		N	118.5	156.6a	2982b	683b	4.4b
		P	118.5	152.3a	3370b	781b	5.1ab
		NP	118.5	153.2a	4033a	947a	6.5a
Potato	2005	NF	262.2	253.5b	2948c	2156c	8.5c
		N	262.2	254.3b	3582ab	2675ab	10.5ab
		P	262.2	257.4ab	3270bc	2455b	9.6bc
		NP	262.2	262.4a	3818a	2896a	11.1a
Pea	2006	NF	88.5	115.7b	955b	416c	3.6b
		N	88.5	119.4b	954b	427c	3.7b
		P	88.5	123.7ab	1188a	496b	4.0ab
		NP	88.5	130.3a	1303a	560a	4.3a
Spring wheat	2007	NF	225.5	231.7a	3171b	803b	3.5b
		N	225.5	243.5a	1740c	412c	1.7c
		P	225.5	231.7a	4910a	1150a	5.0a
		NP	225.5	231.0a	4997a	1172a	5.1a
Potato	2008	NF	201.5	191.3a	882c	796c	4.1c
		N	201.5	190.7a	2041b	1565b	8.2b
		P	201.5	187.7a	620d	505d	2.7d
		NP	201.5	199.6a	2669a	1953a	9.9a
All	Six-year average	NF	174.6	181.4a	2079d	928c	5.1c
		N	174.6	186.3a	2253c	1115b	6.0b
		P	174.6	185.2a	2689b	1101b	6.0b
		NP	174.6	190.2a	3456a	1533a	8.1a

[1]ET = SWS + PGS – SWH, SWS, and SWH mean soil water content in the 0 to 200 cm soil layer at sowing and at harvest times, respectively. The values within a column followed by the same letter did not differ significantly at $p \leq 0.05$.

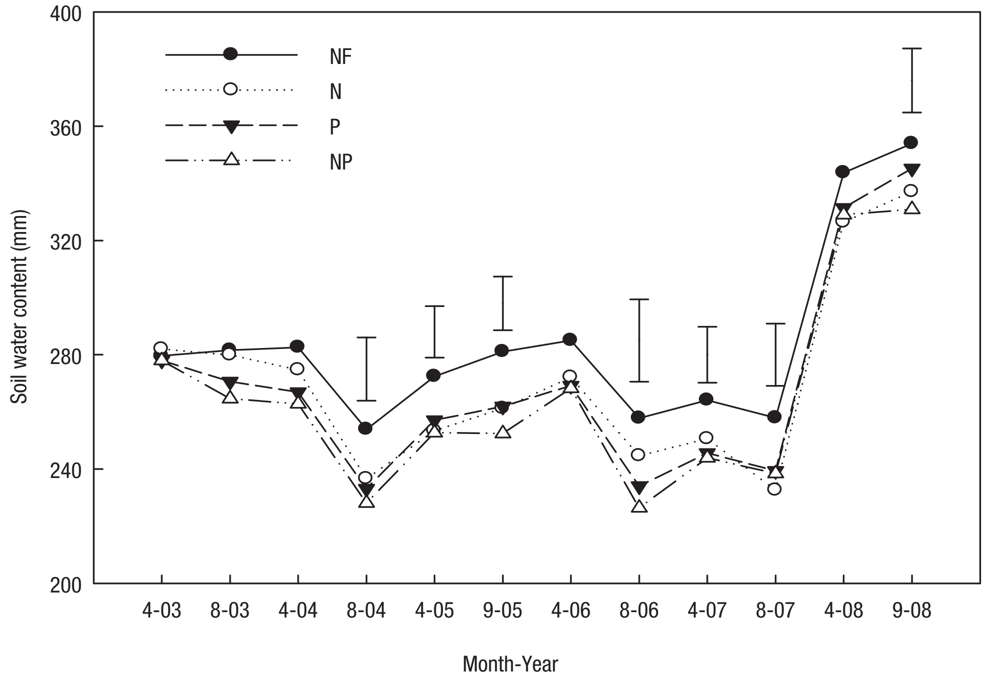

Figure 2. Soil water content at the sowing (SWS) and at harvest (SWH) times from 0 to 200 cm in the various treatments from April, 2003 to September, 2008. Error bars are LSD at $p \leq 0.05$.

in the 0 to 200 cm soil layer at the time of sowing from 2003 to 2008 did not differ significantly among treatments (Fig. 3A). The average soil water content in the 0 to 200 cm soil layer at harvest time from 2003 to 2008 was significantly higher in the NF treatment are as compared with the fertilization treatments, with the order being (mm) as follows: NF (281.0)>N (264.8)>P (264.0)>NP (256.8) (Fig. 3B). Fig. 4 illustrates the soil's moisture profile in the upper 200 cm layer at harvest time in September, 2008, in 20 cm increments for each of the treatments. Following the six-year period, the NP treatment was found to have increased the soil's water depletion in the 100 to 200 cm soil layer more than the other treatments.

In 2003, 2004, and 2008, the NP treatment had significantly higher aboveground biomass than the other treatments. However, in 2005, 2006, and 2007, the aboveground biomass in the N and NP treatments did not differ significantly. The annual average aboveground biomass over the six-year period was 2079, 2253, 2689, and 3456 kg/ha for the NF, N, P, and NP treatments, respectively.

The crop yield was found to be significantly higher in the NP treatment when compared to the other treatments in 2003, 2004, 2006, and 2008 (Table 3). In 2007, the yield of the spring wheat in the N treatment was only 412 kg/ha, compared with the significantly higher values of 803, 1150, and 1172 kg/ha for the NF,

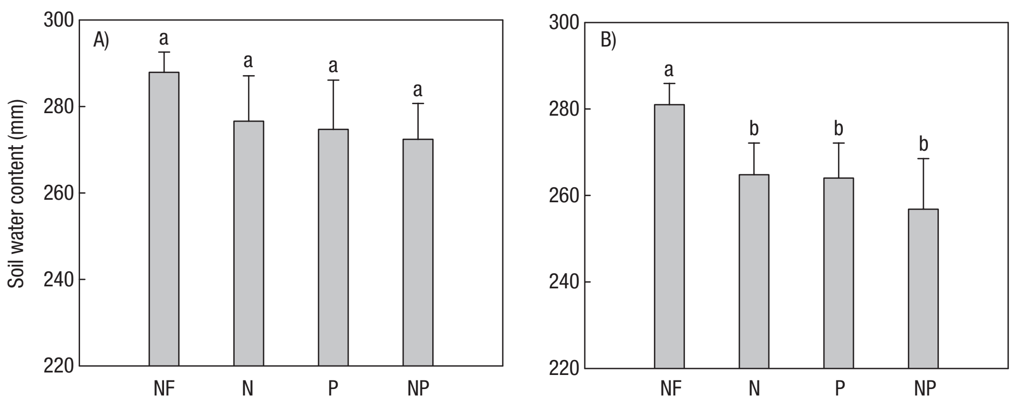

Figure 3. Average soil water content in the 0 to 200 cm soil layer at sowing (A) and at harvest (B) times in the various treatments from 2003 to 2008. The different letters indicate significant differences at $p \leq 0.05$. The values are given as means ± standard deviation (n = 3).

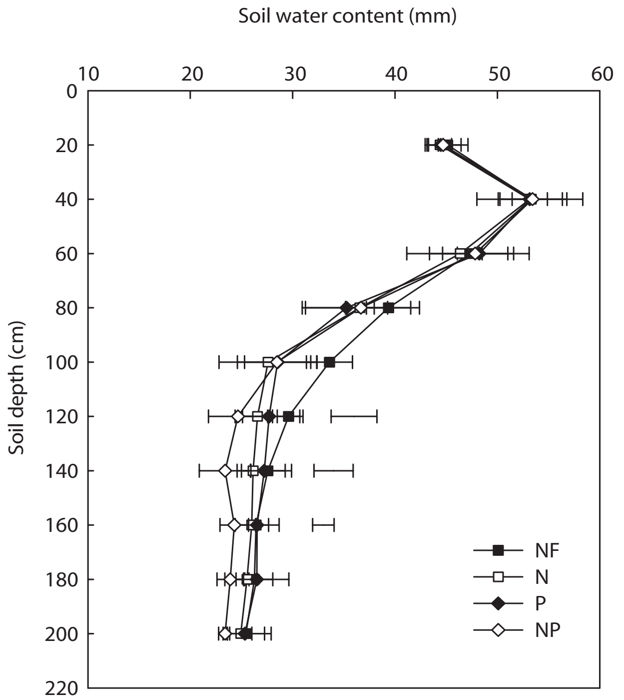

Figure 4. Soil moisture profile in the upper 200 cm layer in 20 cm increments for each of the treatments in September, 2008. The values are given as means ± standard deviation (*n* = 3). The bars represent the LSD at *p*≤0.05.

P, and NP treatments, respectively. In 2008, the potato yield in the P treatment was only 505 kg/ha, compared with the significantly higher values of 796, 1565, and 1953 kg/ha for the NF, N, and NP treatments, respectively. The annual average yields of the field pea crops during the entire experimental period were 635, 677, 858, and 1117 kg/ha for NF, N, P, and NP treatments, respectively. The annual average yields were 673, 547, 966, and 1056 kg/ha for the spring wheat for NF, N, P, and NP treatments, respectively. Meanwhile, for the potato crops, it was 1476, 2120, 1480, and 2424 kg/ha for NF, N, P, and NP treatments, respectively. The annual average crop yields over the six-year period were 928, 1115, 1101, and 1533 kg/ha for NF, N, P, and NP treatments, respectively. Over the six years of the study, the WUE of the crop yields was the highest in the NP treatment, and the lowest in the NF treatment (Table 3). The annual average WUE over the six-year period was 5.1, 6.0, 6.0, and 8.1 kg/ha/mm for the NF, N, P, and NP treatments, respectively.

The yield of the field pea crops in 2003 was significantly higher (*p*≤0.05) than that in 2006 for all of the treatments. The yield of the spring wheat crops in 2007 was significantly higher (*p*≤0.05) than that in 2004 for the NF, P, and NP treatments, and the yield of the potato crops in 2005 was significantly higher (*p*≤0.05) than that of 2008 in all of the treatments (Table 4).

Nitrogen and phosphorus input and uptake by the plant tissues

Over the six years, total N input by fertilizer application was 0, 420, 0 and 420 kg/ha and total N uptake by crops was 197.6, 240.3 245.8 and 363.3 kg/ha for the NF, N, P and NP treatments, respectively (Table 5). Over the six-year period, the total P input by fertilizer application were 0, 0, 94.2, and 94.2 kg/ha, and the total P uptake by the crops were 20.2, 23.5, 33.8, and 45.4 kg/ha for the NF, N, P, and NP treatments, respectively.

Soil properties

During the six-year study, the AP was significantly higher in the P and NP treatments, when compared with the NF and N treatments. The AP in the NF and N treatments decreased rapidly over time (Fig. 5). The AP was 5.3 and 5.4 mg/kg for the NF and N treatments, respectively, prior to the crops being sown in 2003. After six years, the soil AP (Olsen) content was found to be only 3.4 and 3.0 mg/kg in the NF and N treat-

Table 4. Effects of crop rotation on the crop yields in a three-year rotation of field pea-spring wheat-potato from 2003 to 2008.

Crop	Year	PGS (mm)	NF (kg/ha)	N (kg/ha)	P (kg/ha)	NP (kg/ha)
Field pea	2003	151.2	854a	927a	1220a	1674a
	2006	88.5	416b	427b	496b	560b
Spring wheat	2004	118.5	542b	683a	781b	947b
	2007	225.5	803a	412b	1150a	1172a
Potato	2005	262.2	2156a	2675a	2455a	2896a
	2008	201.5	796b	1565b	505b	1953b

The values within a column followed by the same letter do not differ significantly at *p*≤0.05. PGS: precipitation during the growing seasons.

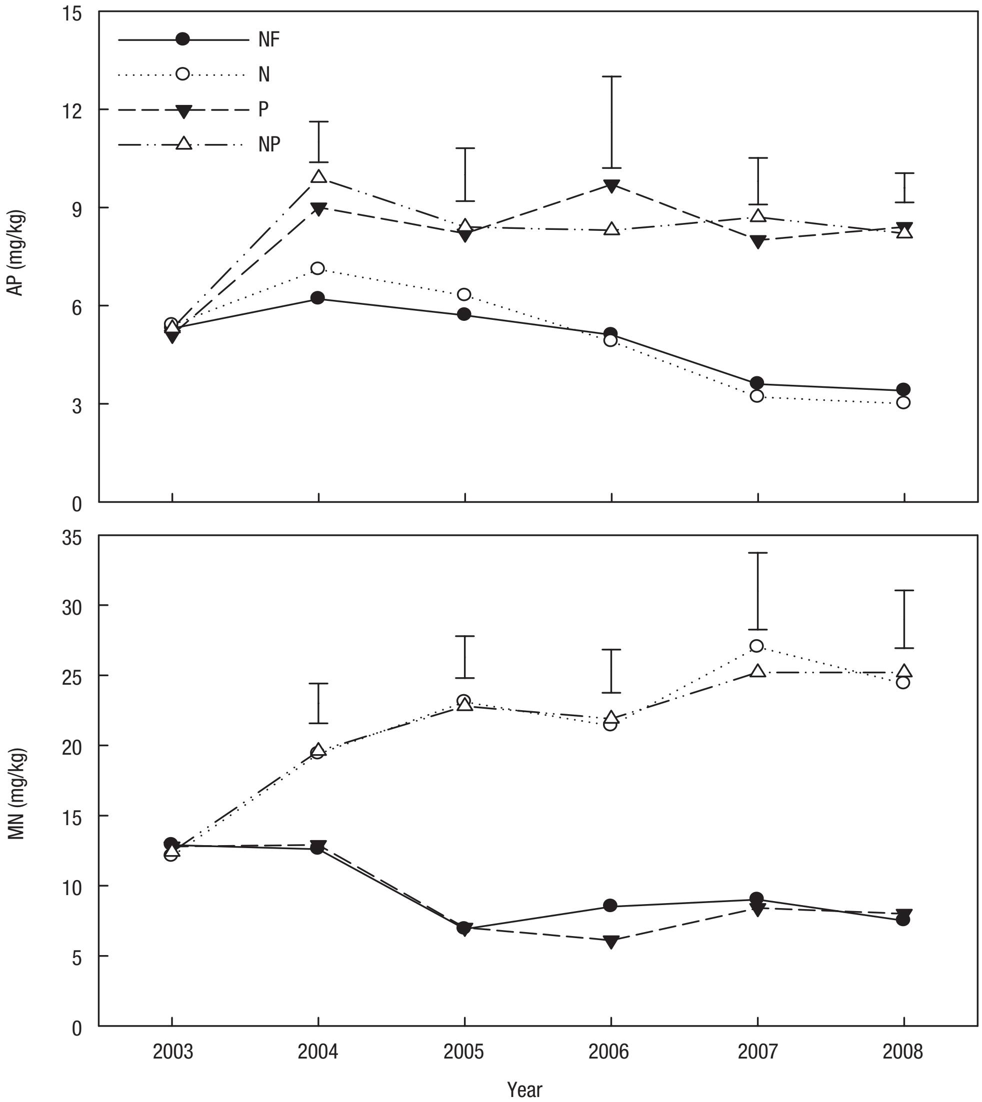

Figure 5. Soil available P (AP; Olsen method) and mineral N (MN) in the 0 to 20 cm soil layer in the various treatments over the experimental period. The error bars represent the LSD at $p \le 0.05$.

ments, respectively. The mineral N (MN) was significantly higher in the N and NP treatments, when compared to the NF and P treatments, during the six-year study. The MN was 12.9 and 12.8 mg/kg for the NF and P treatments, respectively, prior to the crops being sown in 2003. Following the six-year period, the soil's MN was determined to be only 7.5 and 8.0 mg/kg in the NF and P treatments, respectively.

Relation between the crop yields and the precipitation within the growing seasons and soil nutrients

Significant positive correlations ($p \le 0.05$) were observed between the crop yields of the field pea and potato and the precipitation in all of the growing seasons (Fig. 6). The path analyses showed that the spring wheat yield was mainly affected by the soil's available P content and the precipitation in all of the growing seasons, and the potato yield was mainly affected by the soil's mineral N content and the precipitation in all of the growing seasons (Table 6).

Discussion

The precipitation level is one of the key factors which limits agricultural production in semi-arid areas. Gao *et al*. (1999) determined that the winter wheat yield increased by 120 to 180 kg/ha for every 10 mm increase in the available soil water content on the Loess Plateau, China. Wheat has a developed root system, with roots at the 120 cm soil layer even when the annual precipitation is only 239.9 mm in a semi-arid area

Table 5. Nitrogen and phosphorus input and uptake of the plant tissues in the various treatments during the six-year experimental study.

Crop	Year	Treatments	N (kg/ha)		P (kg/ha)	
			Input	Uptake	Input	Uptake
Pea	2003	NF	0	48.0c	0	2.0c
		N	70	54.8c	0	2.5bc
		P	0	67.7b	15.7	3.3b
		NP	70	98.5a	15.7	5.2a
Spring wheat	2004	NF	0	23.5c	0	5.8c
		N	70	31.7b	0	8.6bc
		P	0	31.5b	15.7	9.9b
		NP	70	45.2a	15.7	13.9a
Potato	2005	NF	0	53.7b	0	2.6c
		N	70	69.3a	0	3.8a
		P	0	60.4b	15.7	3.1b
		NP	70	75.8a	15.7	4.2a
Pea	2006	NF	0	23.3c	0	1.0c
		N	70	25.6c	0	1.3b
		P	0	29.3b	15.7	1.4b
		NP	70	36.4a	15.7	1.8a
Spring wheat	2007	NF	0	32.2b	0	8.0b
		N	70	18.3c	0	5.2b
		P	0	44.9a	15.7	15.3a
		NP	70	53.9a	15.7	17.3a
Potato	2008	NF	0	16.9c	0	0.9c
		N	70	40.5b	0	2.2b
		P	0	11.9c	15.7	0.7c
		NP	70	53.5a	15.7	3.0a
All	Six-year total	NF	0	197.6c	0	20.2c
		N	420	240.3b	0	23.5c
		P	0	245.8b	94.2	33.8b
		NP	420	363.3a	94.2	45.4a

The values within a column followed by the same letter did not differ significantly at $p \le 0.05$.

(Li *et al*., 2006). The years of intensive farming using a winter wheat monocrop system, which increases the use of fertilizers, have led to the gradual depletion of the soil's water content at the 0 to 300 cm soil depth on the Loess Plateau (Huang *et al*., 2003). In the current study, it was found that the increased productivity with fertilizer applications increased the soil's water depletion during this six-year experiment in a semi-

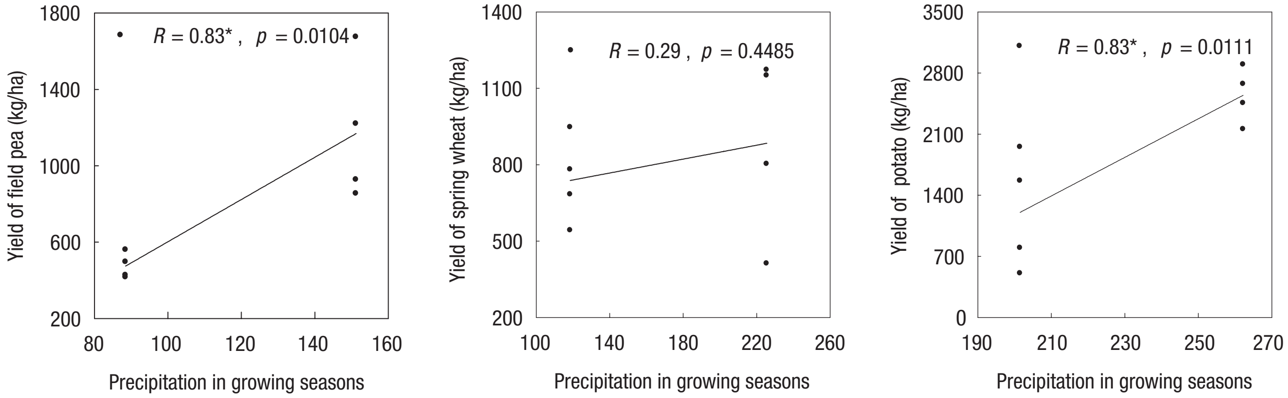

Figure 6. Relationship between the precipitation within the growing seasons and the crop yields in all of the treatments over the experimental period. *R*: correlation coefficients; *: significant at $p \le 0.05$.

Table 6. Path analyses examining the direct and indirect effects of the available P (AP), mineral N (MN), and precipitation during the growing seasons (PGS) on the crop yields. The total effect was estimated from the sum of the direct and indirect effects, where R^2 indicates the proportion of variation explained by the multiple regression models in each case.

Crop	Variable	Direct effect	Indirect effect			Total effect
			$\rightarrow x_1$	$\rightarrow x_2$	$\rightarrow x_3$	
Spring wheat	AP (x_1)	0.9235		0.0071	–0.1856	0.7450
	MN (x_2)	–0.2142	–0.0307		0.0572	–0.1877
	PGS (x_3)	0.5963	–0.2874	–0.0205		0.2884
		R^2=0.90, $p\leq0.05$				
Potato	AP (x_1)	0.0438		0.0025	0.2835	0.3298
	MN (x_2)	0.4977	0.0002		–0.0681	0.4298
	PGS (x_3)	0.8534	0.0146	–0.0397		0.8283
		R^2=0.94, $p\leq0.05$				

arid area. However, the soil's water content did not gradually decrease with time after sowing. The reason was largely due to the low crop yields which can reduce crop water use. In the NP treatment, the increased water depletion of the soil in the 100 to 200 cm soil layer when compared with the other treatments, which was due to the high ET caused by the high crop yield during the growing seasons. Liu *et al.* (2009) reported that increased maize productivity from ridge–furrowing and plastic mulching practices led to significant soil water depletion in the 100 to 200 cm soil layer in the same region. These results suggested that the generation of high crop yields in semi-arid areas will tend to increase the water depletion in the deep soil layers.

In China, rain-fed farming systems account for ~$25\cdot10^6$ ha, which are mainly located in the semi-arid Loess Plateau (Deng *et al.*, 2006). The improvement of crop WUE in the Loess Plateau dryland areas is crucial for sustainable crop production, as well as local food security (Zhang *et al.*, 2014). In this study, it was found that the fertilization practices improved the WUE of the crops by increasing crop yields. However, it increased the soil's water depletion in the deep soil layers. The findings of this study suggest that agro-ecosystems are not sustainable in water-limited environments, if only the pursuit of a higher crop WUE by the application of fertilization is the focus, and the decreasing of the soil's water depletion is ignored. In order to reduce the soil's water depletion and increase the WUE, rainwater harvesting practices (*e.g.* ridge-furrow rainwater harvesting with plastic film) should be applied in this type of rotation system.

In this study, significant positive correlations ($p\leq0.05$) were observed between the crop yields of the field pea and potato and the precipitation in all of the growing seasons (Fig. 6). The changes in the crop yields during the years of this study were mainly affected by the growing seasons' precipitation. Although it was determined that the growing season precipitation was higher in 2007 than in 2004, the yield of the spring wheat in the N treatment was found to be significantly lower in 2007 when compared to that of 2004. In 2007, the yield of the spring wheat was significantly lower in the N treatment when compared with the other treatments, and no significant differences were observed in the P and NP treatments. The path analyses indicated that the available P was essential for increasing the productivity of the spring wheat (Table 6). After four years in this study, the total P uptake was 11.4, 16.2, 17.7, and 25.1 kg/ha for the NF, N, P, and NP treatments, respectively. Due to there being no P fertilization, the soil's available P content was lowest in the N treatment before sowing 2007. The soil mineral N content changed little, and remained very poor after the planting of the field pea crop, which indicated that the N fixation by the field pea was very low in this semi-arid area. Zhu *et al.* (1982) reported that 60% of field pea crops have no N fixation ability in the semi-arid areas of China. Prior to sowing in 2007 (field pea was planted in 2006), the N treatment had 27 mg/kg mineral N, and 3.2 mg/kg available P, and the P treatment had 8.4 mg/kg of mineral N, and 8.0 mg/kg of available P. The yield of spring wheat was 412 and 1150 kg/ha for the N and P treatments, respectively. These results indicated that the P fertilizer was more important for improving wheat yield than N fertilizer in calcareous soil in a semi-arid agro-ecosystem. In this study, it was found that the field pea yield was significantly higher in the P treatment than in the N treatment during the average (2003) and dry (2006) years, which indicated that the application of P fertilizer was essential for improving the productivity of field pea crops.

In this study, it was determined that the input of P fertilizer could potentially maintain the soil's AP, while the soil AP decreased rapidly in the treatments without the input of P fertilizer. In this region, the lack of P reserves in the soil was not the main factor. The less available forms of Ca_{10}-P, O-P and Ca_8-P occupied ~86% of the total inorganic P (Wang *et al*., 2005). At the same time, the low microbial biomass activity also limited the decomposability of organic P, and reduced the AP of the soil (Wang *et al*., 2009). Therefore, the input of P fertilizer was pivotal for increasing the productivity of the spring wheat and field pea crops in the calcareous-alkaline soil.

In 2008, the potato crop yield was significantly lower in the P treatment when compared with the other treatments. The path analyses showed that the availability of P and mineral N, along with the precipitation levels during the growing seasons, explained as much as 94% of the yield variability for the potato crops ($p \leq 0.05$), and that the potato yield was mainly affected by the soil's mineral N content (Table 6). After five years of the experiment, the total N uptake by the crops was 180.7, 199.7, 233.8, and 309.8 kg/ha for the NF, N, P, and NP treatments, respectively. Due to there being no application N fertilizer and the large N uptake by crops, the MN content of the soil in the P treatment was only found to be 8.0 mg/kg. The deficiency of MN, along with the low soil water content in 2008, led to low potato yields in the P treatment. This indicated that N input by application of fertilizer was crucial for increasing the potato crop yield. In this study, MN content in the NF treatment was also very low prior to sowing in 2008. However, the high soil water content in the 0 to 200 cm soil layer led to a significantly higher potato yield when compared with the P treatment.

As conclusions, in this semi-arid agro-ecosystem with calcareous soil, the changes in the crop yields during the years of this study were mainly affected by the precipitation during the growing season. Also, the input of P fertilizer was found to be essential for increasing the crop yields in spring wheat and field pea, while the input of N fertilizer was essential for increasing the potato crop yield. The increased productivity from fertilizer application may increase the soil's water depletion in the deep soil layers. In order to obtain sustainable high crop yields, rainwater harvesting practices should be applied to this type of rotation system.

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